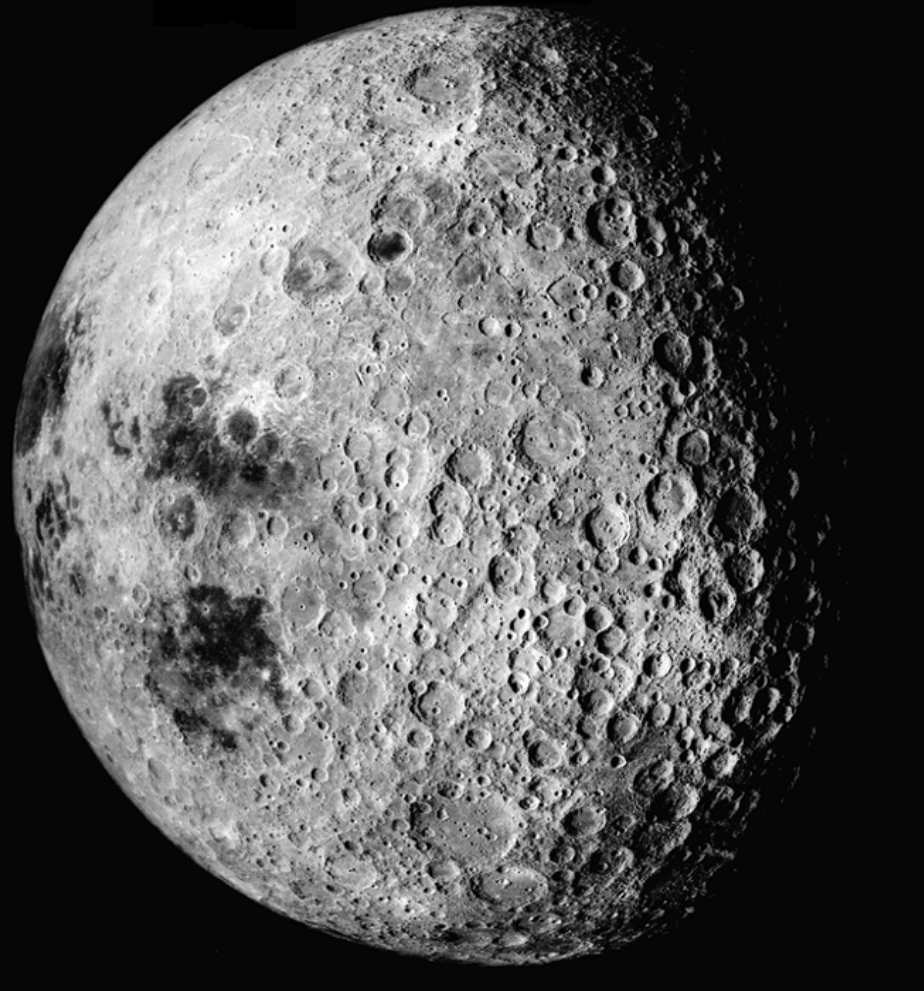


Exploration and Science of the Moon



Caleb Fassett
NASA Marshall Space Flight Center
March 23, 2019

The Moon: Exploration

- Telescopic Phase: Galileo, Huygens, etc.
- Photography: Mid-1800's
- Robotic Orbiter (Earth): Sputnik - 1957
- Human Orbiting (Earth): Gagarin - 1961
- Kennedy's National Goal
- Space Missions: The US-USSR Space Race

- 1959

Luna 3 (Farside)

- 1964

Ranger 7, 8, 9

- 1966

Luna 9 (Soft Lander)

- 1966

Surveyor I, III, V, VI, VII

- 1966-1967

Lunar Orbiter I-V

- 1969-1972

Apollo 11-17

- 1970-1976

Luna 16, 20, 24

- 1970

Lunakhod I, II, Zond spacecraft

- 1990's

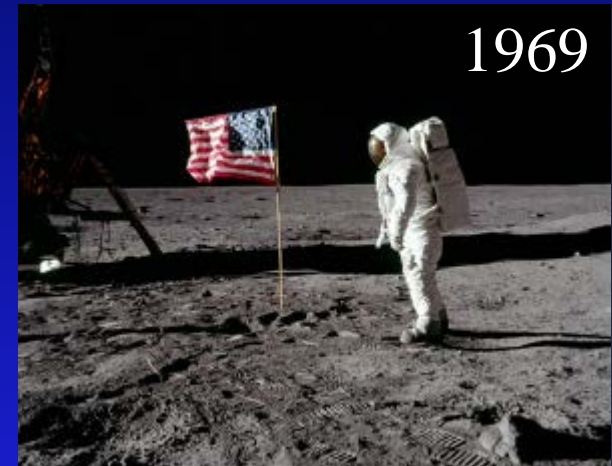
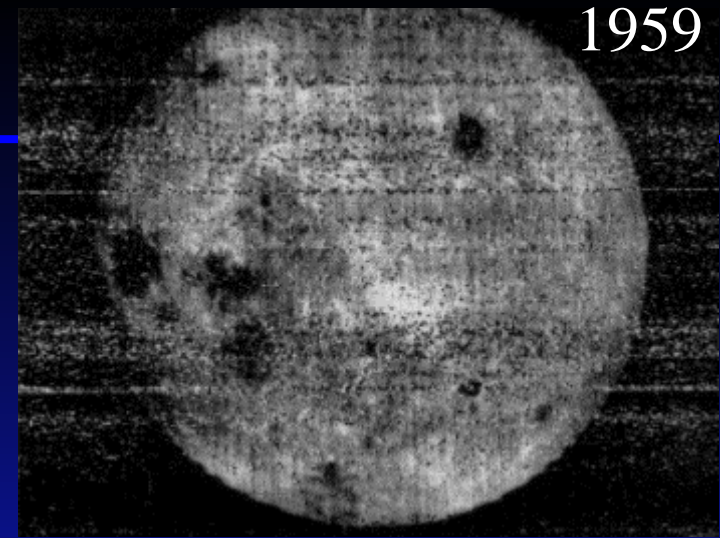
Galileo, Clementine, Lunar Prospector

- 2000-2019

USA, Japanese, Indian, Chinese, and Israeli missions

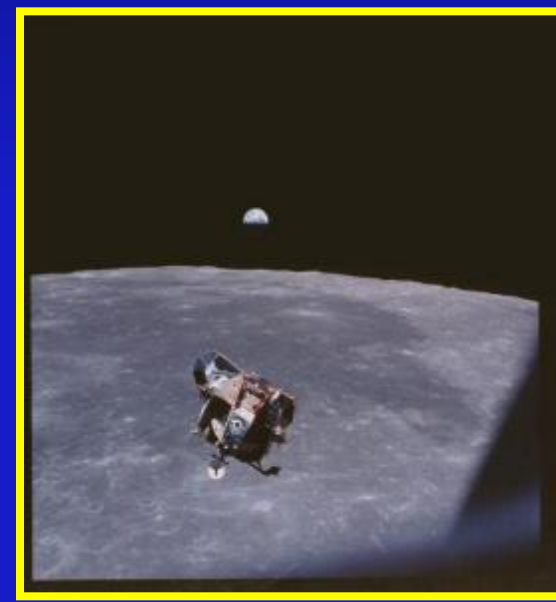
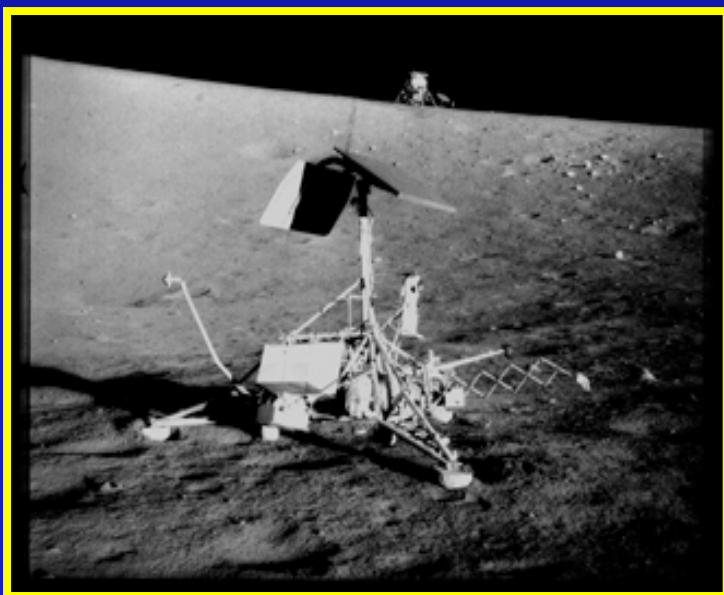
- Next steps:

Commercial landed missions, return of humans?





The Moon: Exploration



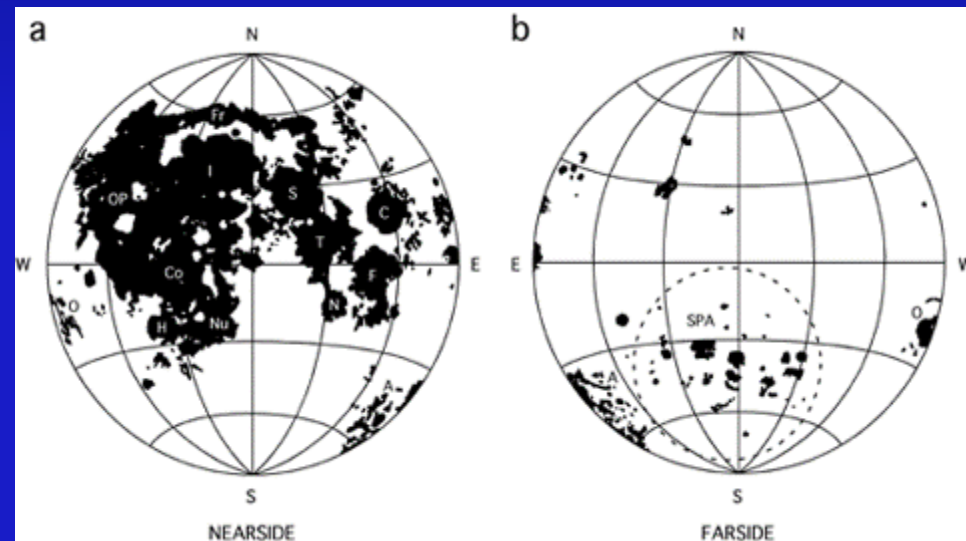
The Moon: Exploration

- After Apollo 17 (1972) and Lunar 24 (1976), *no* scientific missions to the Moon (human or robotic) again until 1994.
 - Recent years have seen an uptick in activity:
 - Clementine: 1994
 - Lunar Prospector: 1998
 - Smart-I (Europe): 2003
 - SELENE / Kaguya (Japan): 2007
 - Chandrayaan-I (India): 2008
 - Lunar Recon Orbiter: 2009
 - LCROSS: 2009
 - Chang'e 2 (China): 2010
 - GRAIL: 2011
 - LADEE: 2013
 - Yutu/Chang'e 3 (China) 2014
 - Yutu 2/Chang'e 4 (China) 2019
 - Beresheet (Israel) 2019
- Coming Soon:*

 - CLPS landers 2019-
 - Mid-sized landers [notional] (2022)
 - Human-class lander [notional](2028)

The Moon: A User's Guide

- Two Major Provinces:
 - Highlands, Maria
- Maria:
 - ~20% of surface (mostly on near-side)
 - Basaltic (volcanic)
 - Albedo: 8-10%
 - 'Young'/Lightly-cratered
- Highlands (or Terra)
 - ~80% of surface
 - Anorthositic
 - Albedo: 12-25%
 - 'Old'/Heavily-Cratered





The Moon: A User's Guide

- Most Important Processes on the Moon:
 - Formation, Differentiation, Magma Ocean
 - Impact Cratering
 - Volcanism



The Moon: Formation

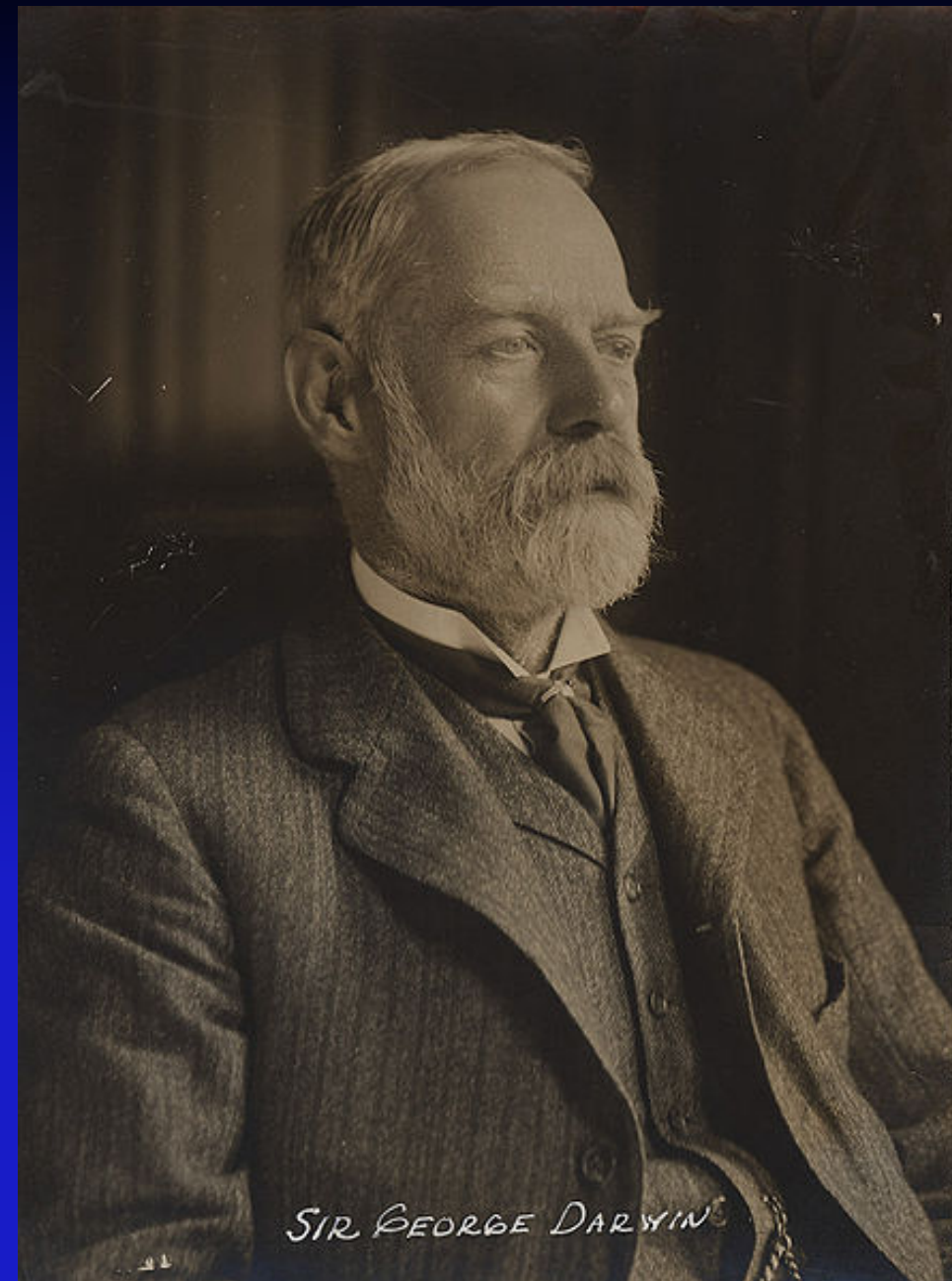
Prior to the Apollo Missions, many scientists believed the Moon formed in the early Solar System by direct accretion from a primordial disk similar to other planets:

- Co-accretion (**sibling**)
 - \oplus and \textcircled{C} formed together

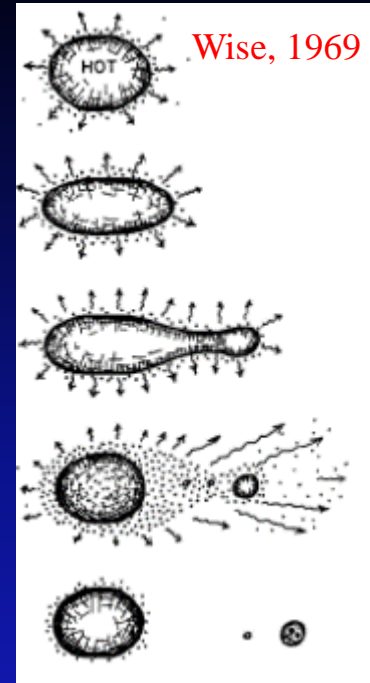
Other ideas:

- Fission (**child**)
 - Fast-spinning \oplus , a blob tore away
- Capture (**cousin**)
 - \textcircled{C} made a close pass to \oplus , captured into orbit
- Giant impact (**angry cousin**)
 - **Proto-** \oplus struck by Mars- sized impactor then Moon forms from debris

George H. Darwin



Fission origin of the Moon



“[People] will always aspire to peer into the remote past to the utmost of their power and the fact that their success or failure cannot appreciably influence their life on Earth will never deter them from such endeavors.”

Fission Origin of the Moon

Likely Problems:

- Classical fission mechanism requires **too much** total angular momentum in the Earth-Moon system
[Think about it: the Earth would have had to be spinning fast enough to tear itself apart! Where does the angular momentum go?]
- Cannot easily account for the fact that the Moon revolves around the Earth in an orbit slightly off the Earth's plane of rotation

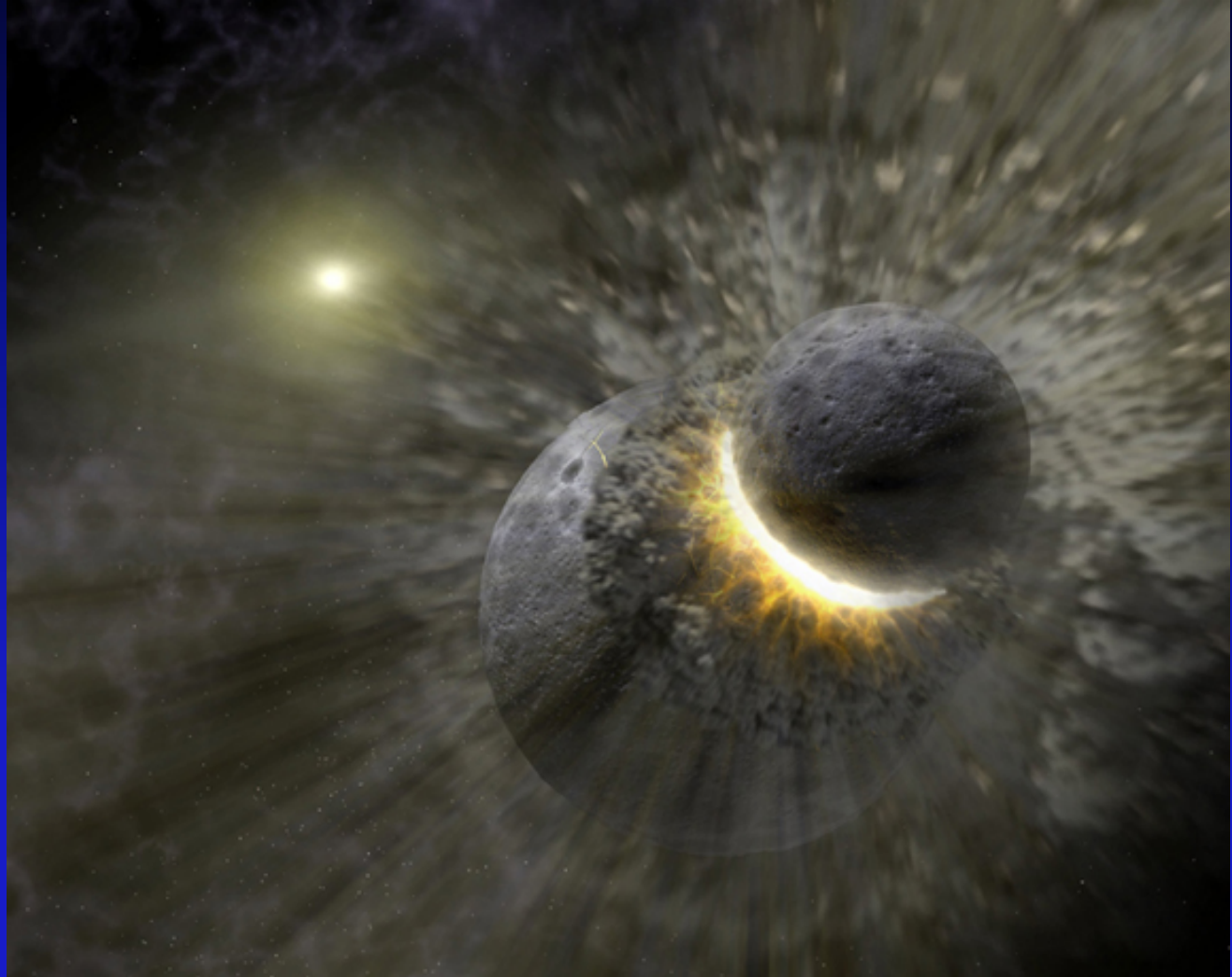
Prior to 2010, most scientists settled on a Giant Impact as the most likely Moon origin hypothesis...

Giant Impact Hypothesis

Canonical model:

A projectile about the size of Mars ($1/10^{\text{th}}$ the M_{Earth}) struck Earth ~ 4.5 - 4.55 Gy.

First proposed by four scientists (1974-1977):
Hartmann, Davis, Cameron, Ward

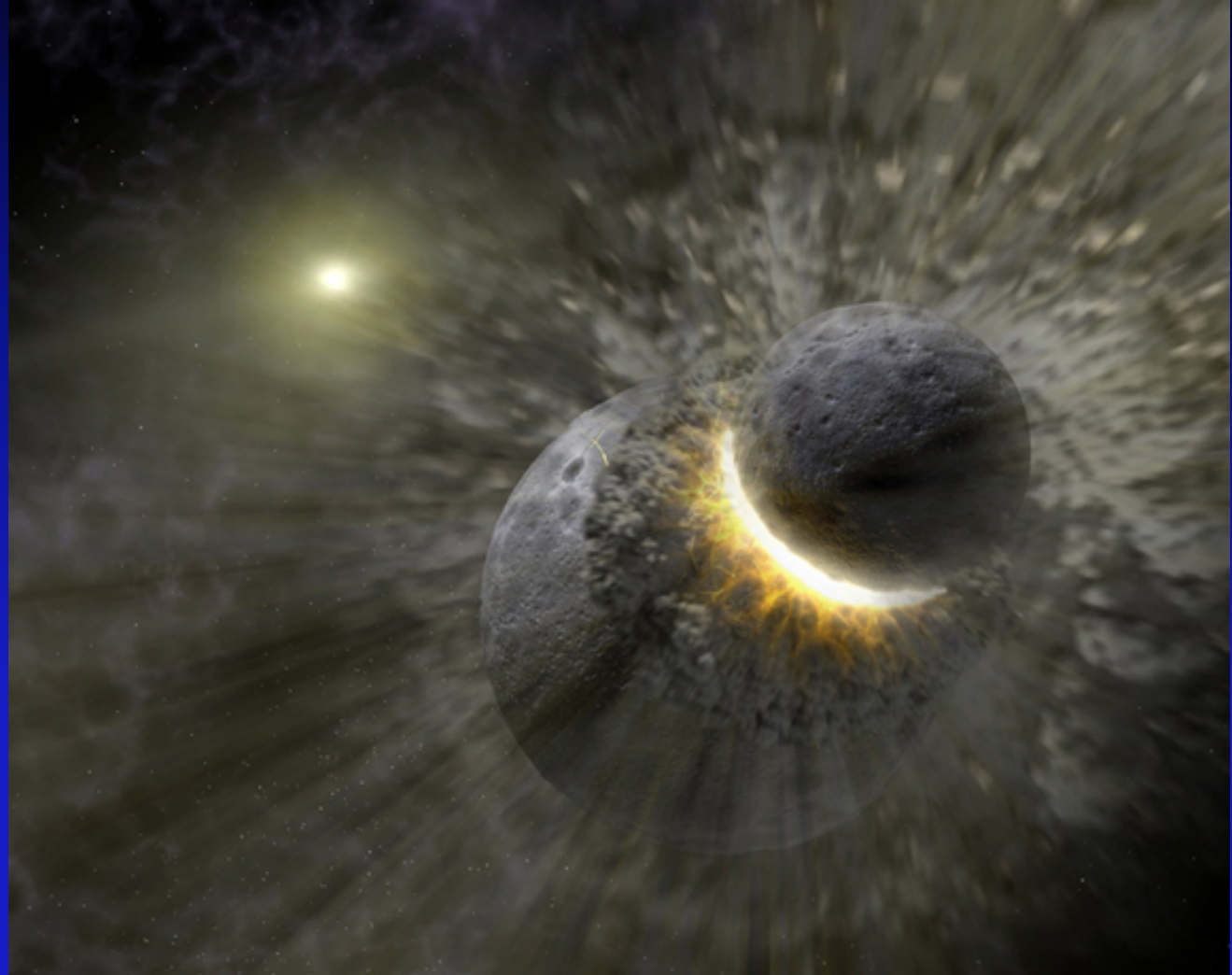


NASA/Artist's Conception

Giant Impact Hypothesis

Material was jettisoned outward, and some fraction of this mass remained in Earth orbit and formed the Moon.

The Moon may be mostly derived from the crust and mantle of the Earth and/or the impacting object.

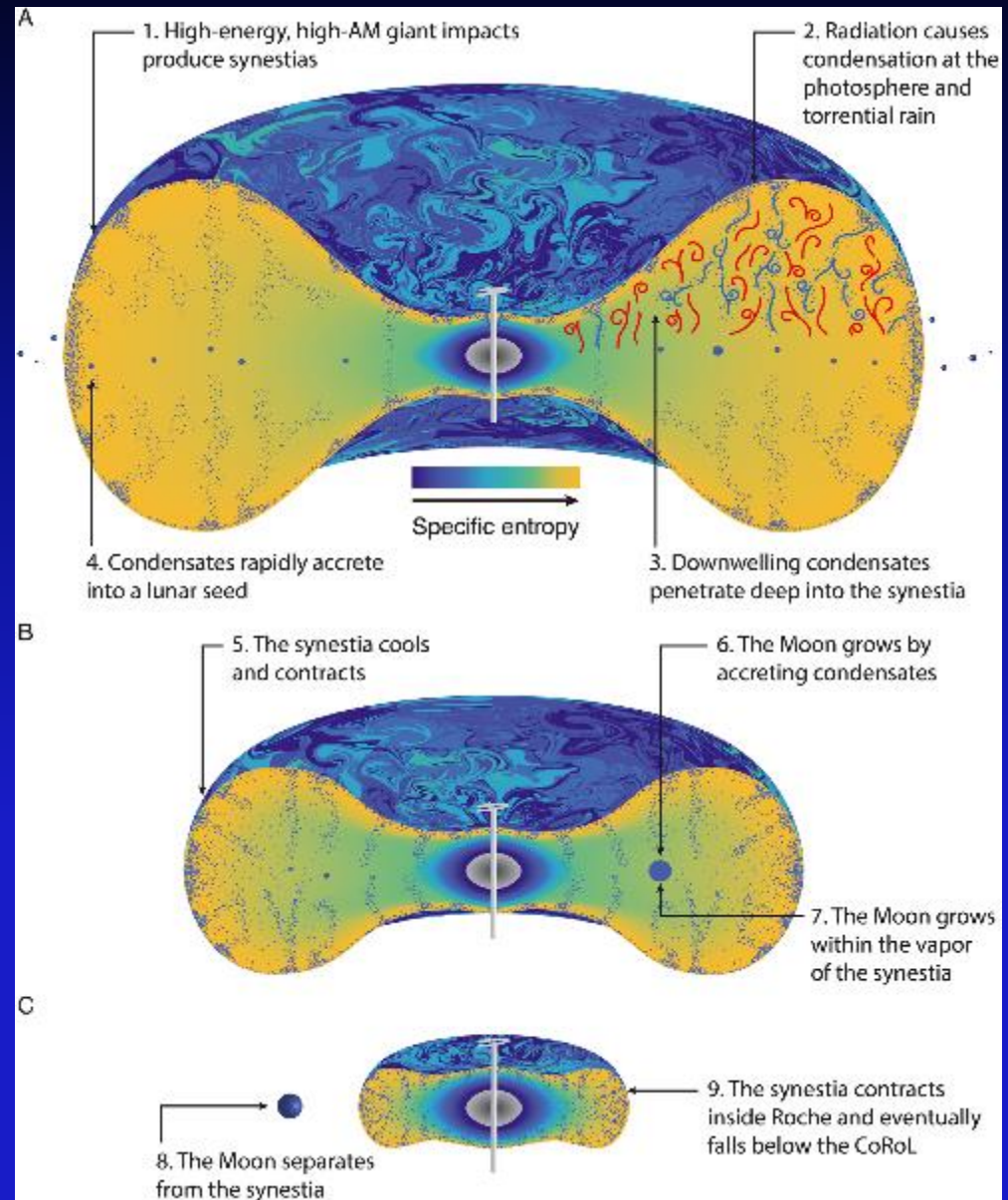


NASA/Artist's Conception

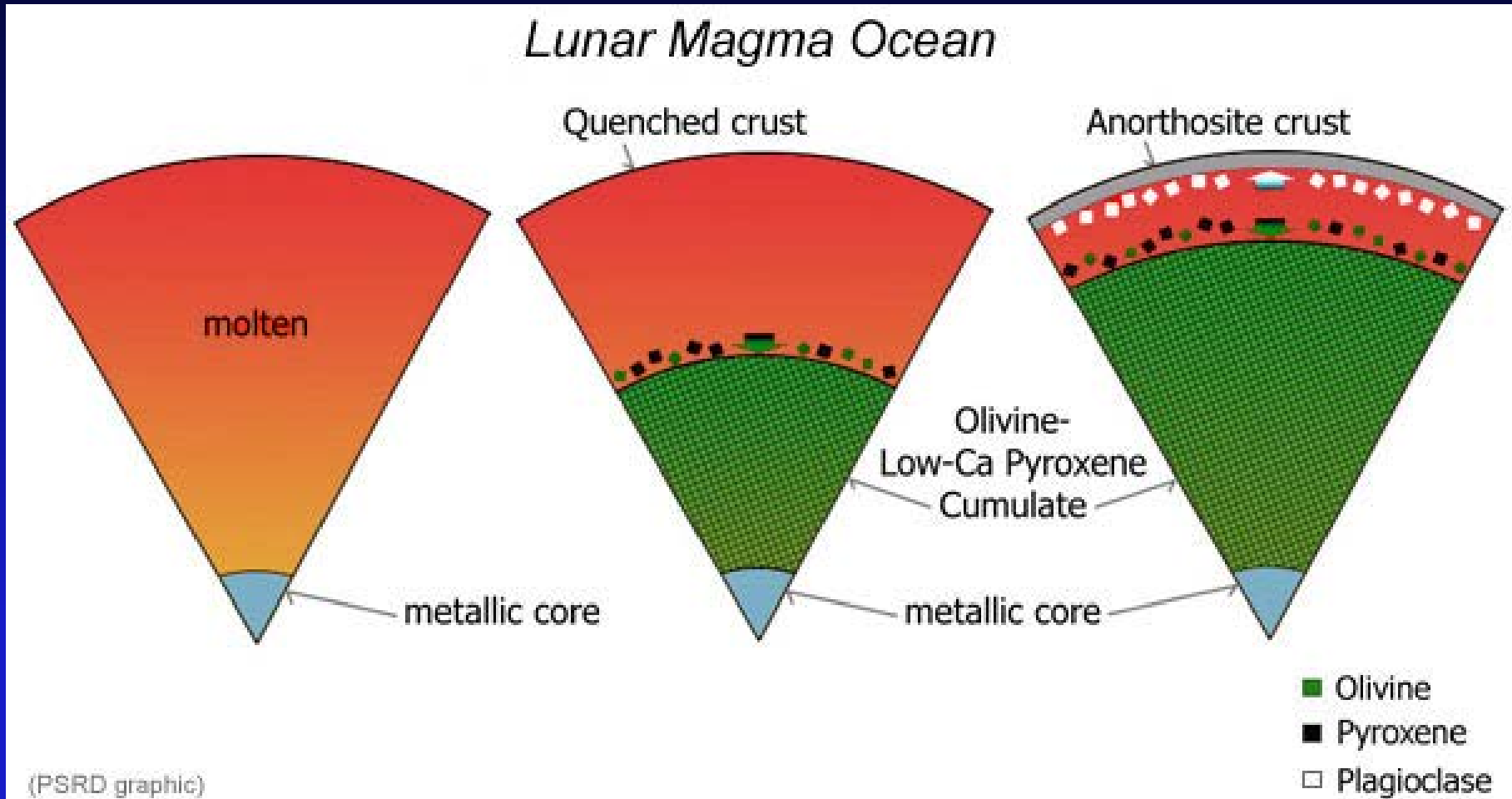
The Earth-Moon Donut: “Synestia”

A new 2017-2018 idea:
A higher energy, high angular momentum impact produces a fast-rotating, donut-shaped disk of silicate vapor, and the Moon condenses out.

A nice feature of this model is that a wide range of giant impact parameters can end in this state (as long as the impact is big enough).



The Moon after Giant Impact: Magma Ocean



Heavy (High Density) Minerals Sink, Light (Low Density) Minerals Float

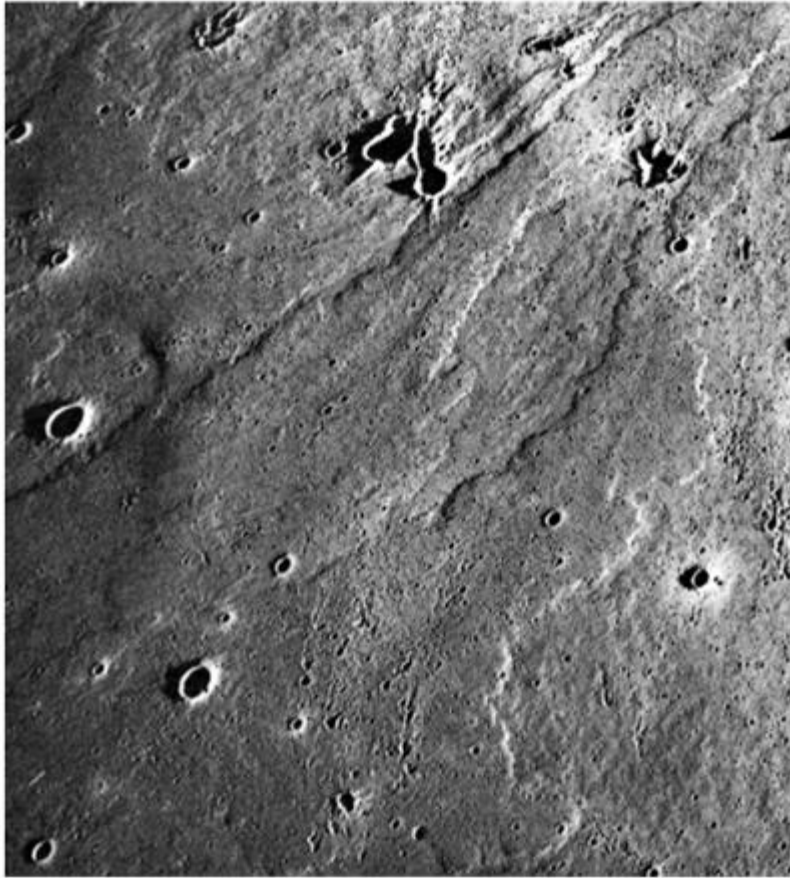


The Moon: Lunar highlands

- Highlands:
 - ‘*Primordial Crust*’
 - Composition: dominated by anorthosite
 - Geology: most influenced by impact cratering



Volcanism and the Maria: Effusive Volcanism



Mare Imbrium



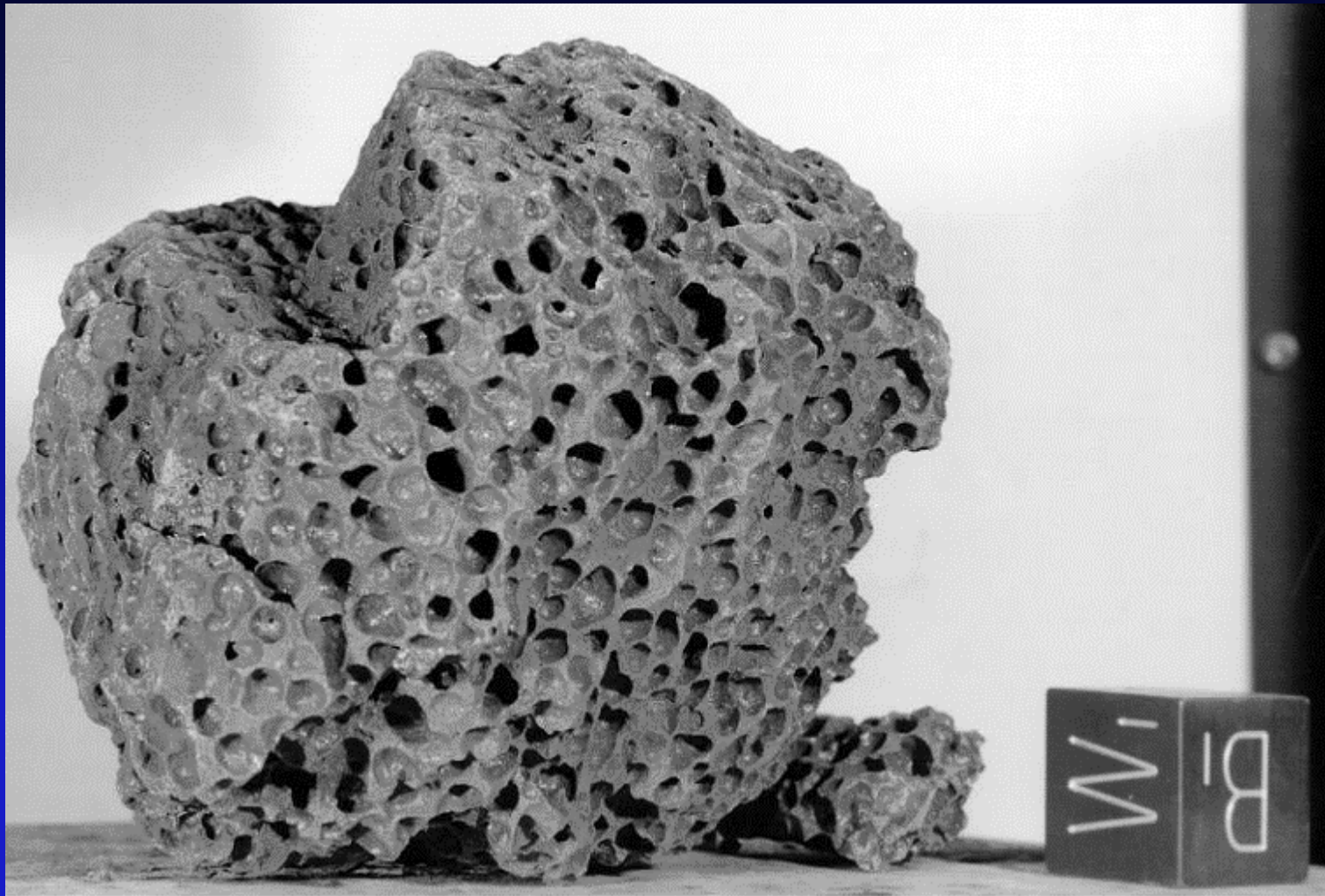
Rimae Prinz

Mare Lava Flows:
Similar to those on Earth

Sinuuous Rilles: High Eruption
Rates; Potentially High Enough
to Erode Rock?

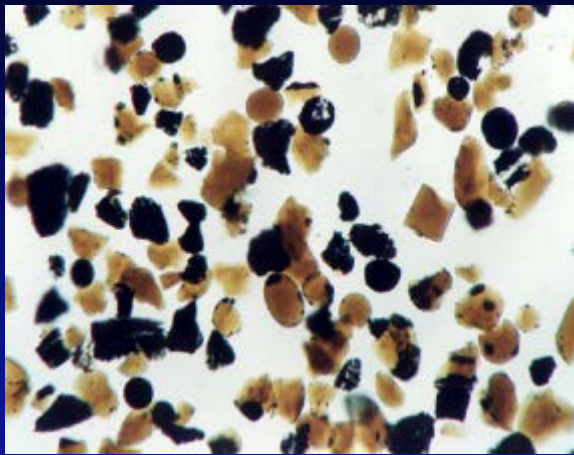


Volcanism and the Maria: Effusive Volcanism



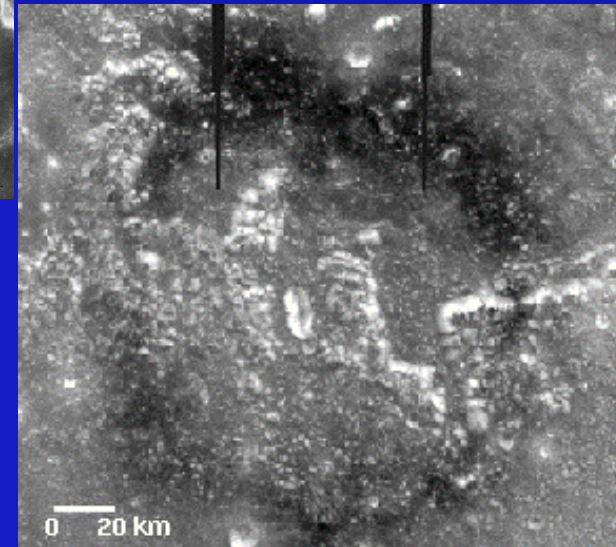
**Vesicular Basalt, Apollo 15
Sample 15556**

Volcanism and the Maria: Explosive Volcanism

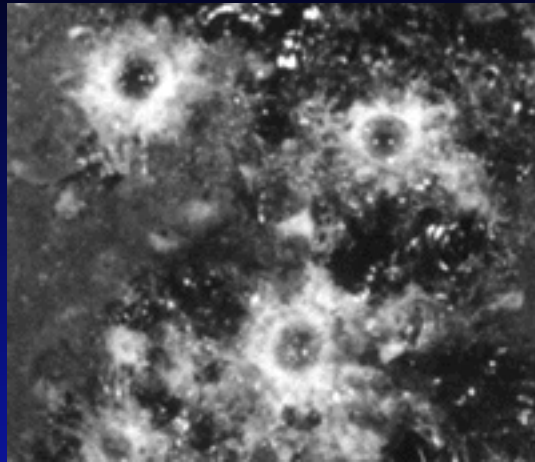


**Apollo 17
Landing Site**

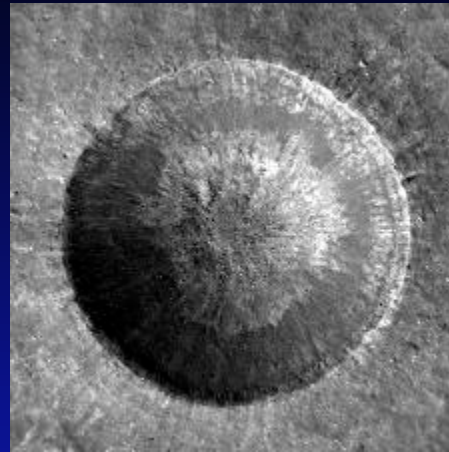
**Dark Pyroclastic Ring
in Orientale Basin**



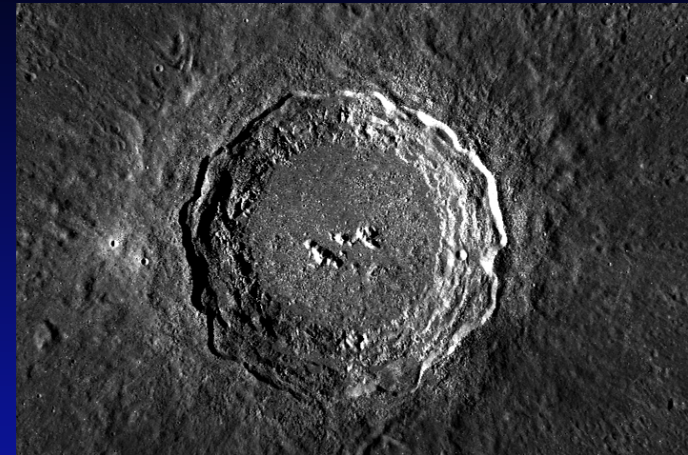
Craters at all scales on the Moon



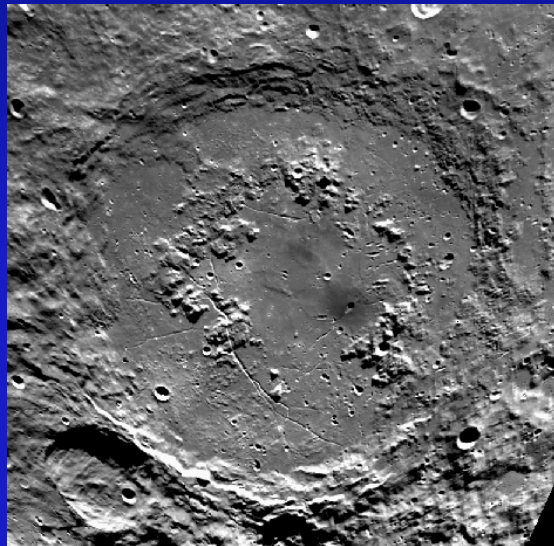
'Zap pits' D~1 mm
(Apollo sample 64455)



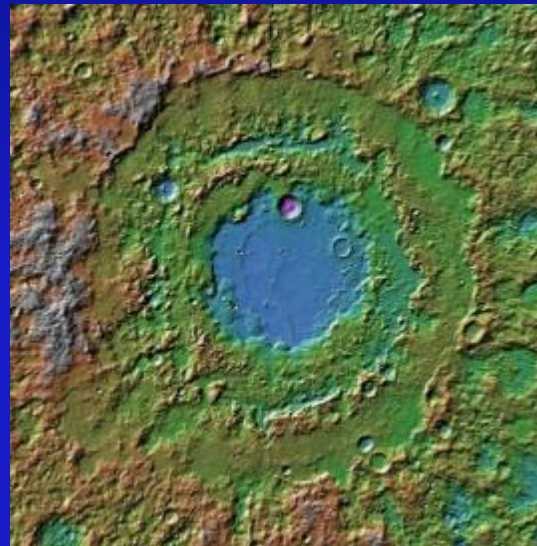
Linne Crater D=2.5 km
(LROC NAC)



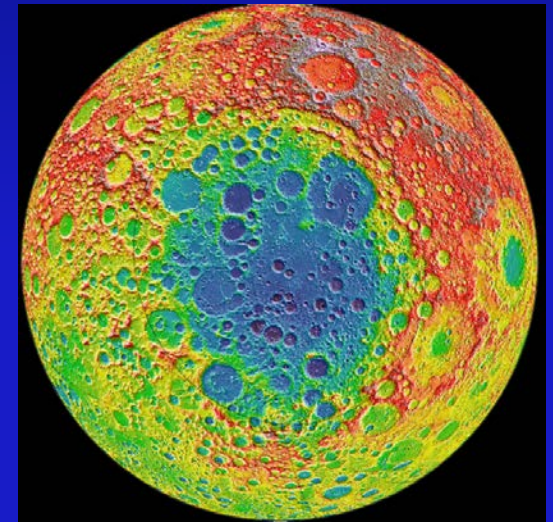
Tycho Crater D=90 km
(Kaguya Terrain Camera)



Schrodinger Basin
D=310 km (Clementine)



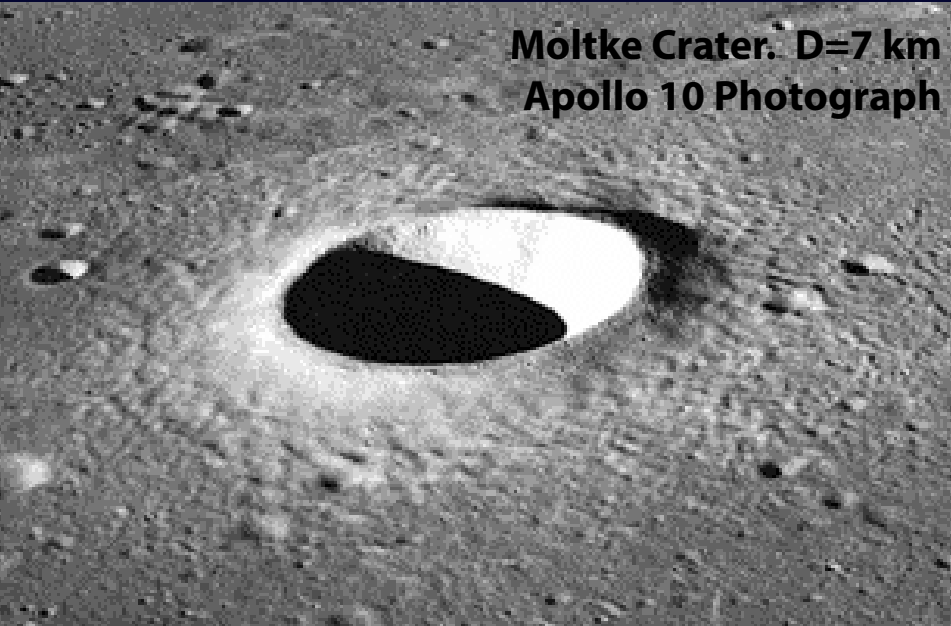
Oriente Basin
D=930 km (LOLA)



South Pole/Aitken Basin
D~2400 x 2000 km (LOLA)

Simple (Bowl-shaped) Craters

Moltke Crater. D=7 km
Apollo 10 Photograph



Meteor Crater. D=1.1 km



Key Characteristics:

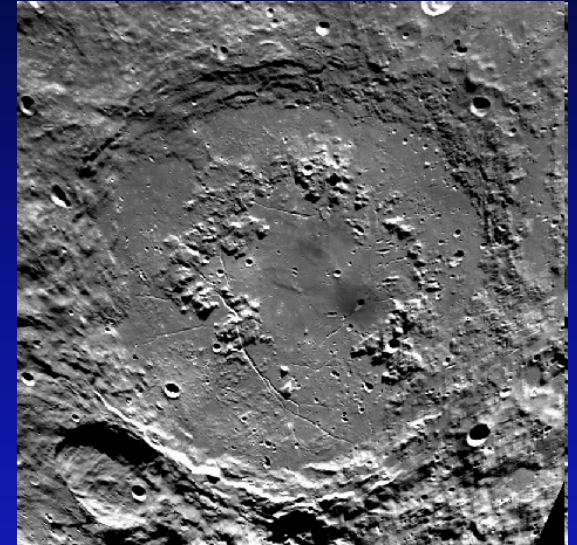
- Generally circular outline (even for oblique impacts);
- Uplifted rim
- Hummocky Ejecta (within 1 crater diameter)

Complex Craters

Tycho Crater on the Moon. D=90 km
Kaguya Terrain Camera



Schrodinger Crater on the Moon .
D=310 km, Clementine

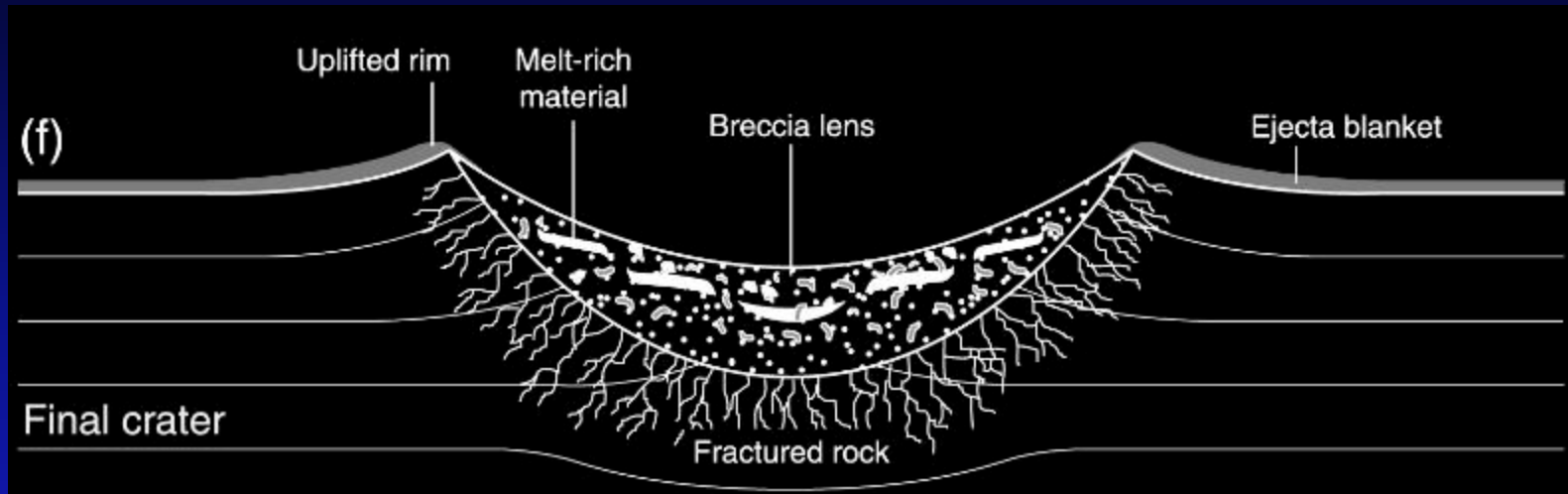


Key Characteristics:

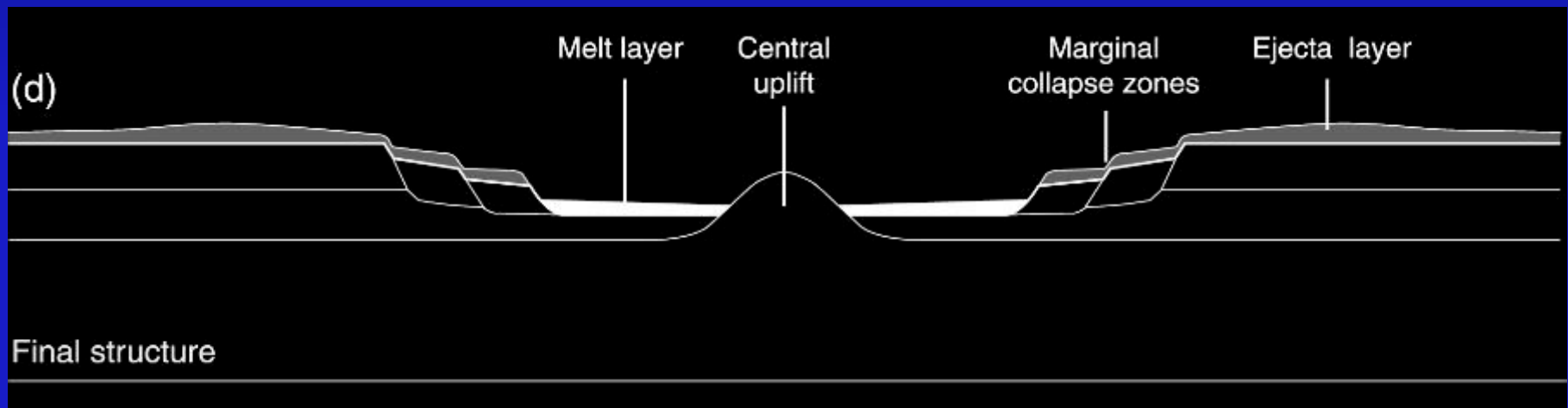
- Central Peak / Central Uplift / Central Ring
- Flat Floor
- Terraced Rim

Idealized Cross-sections

Simple Crater. $D < \sim 20$ km



Complex Crater. $D > \sim 20$ km





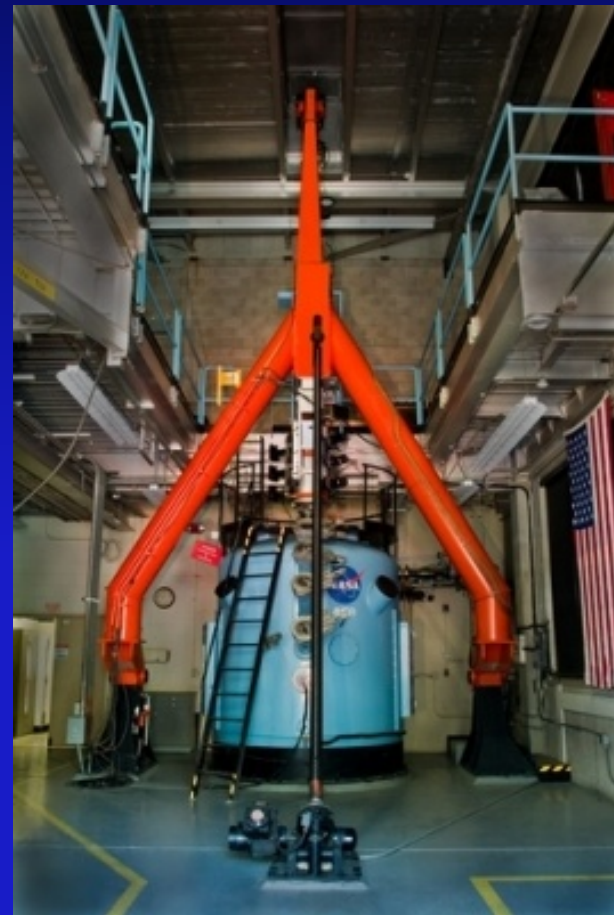
The Impact / Explosion Analogy



Sedan explosion crater, $D \sim 400$ m
Nevada Test Site. 7/5/1962

How do we study impact craters?

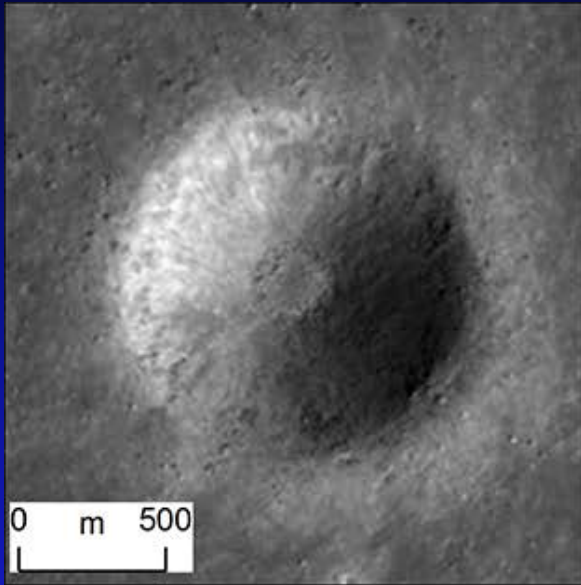
- Controlled Laboratory Experiments:
NASA Ames Vertical Gun Range



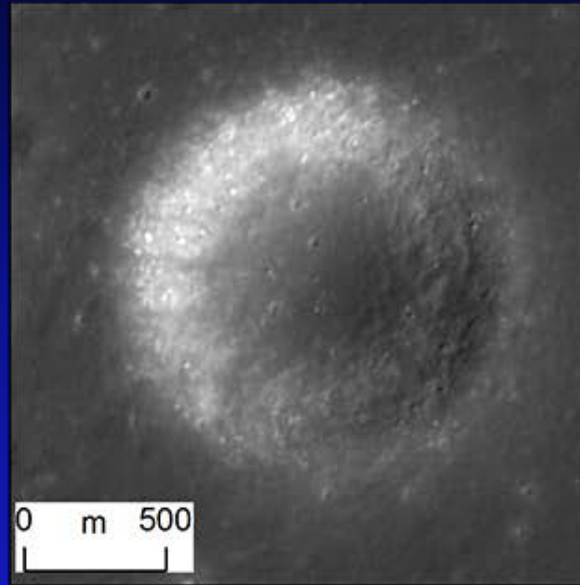




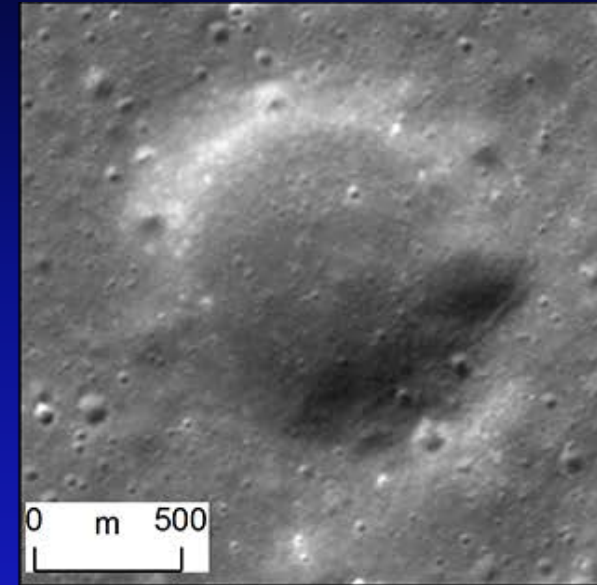
My Lunar Science: *Erosion* on the Moon



Fresh Crater
T~0.01 Ga



Moderately Degraded
T~3 Ga



Very Degraded
T~3.7 Ga

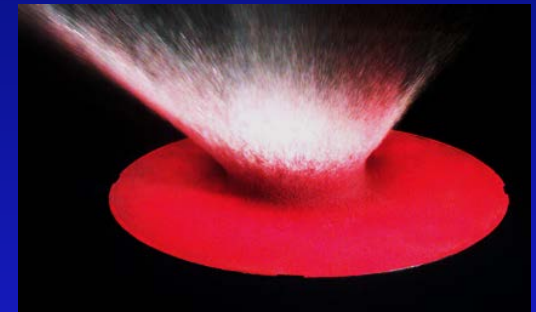
Calibrate the age of craters from their
freshness, to reduce sole reliance on crater
counts.

My Lunar Science: *Erosion on the Moon*

“...[impact cratering] is analogous, but generally at a larger scale, to the effect of a raindrop”

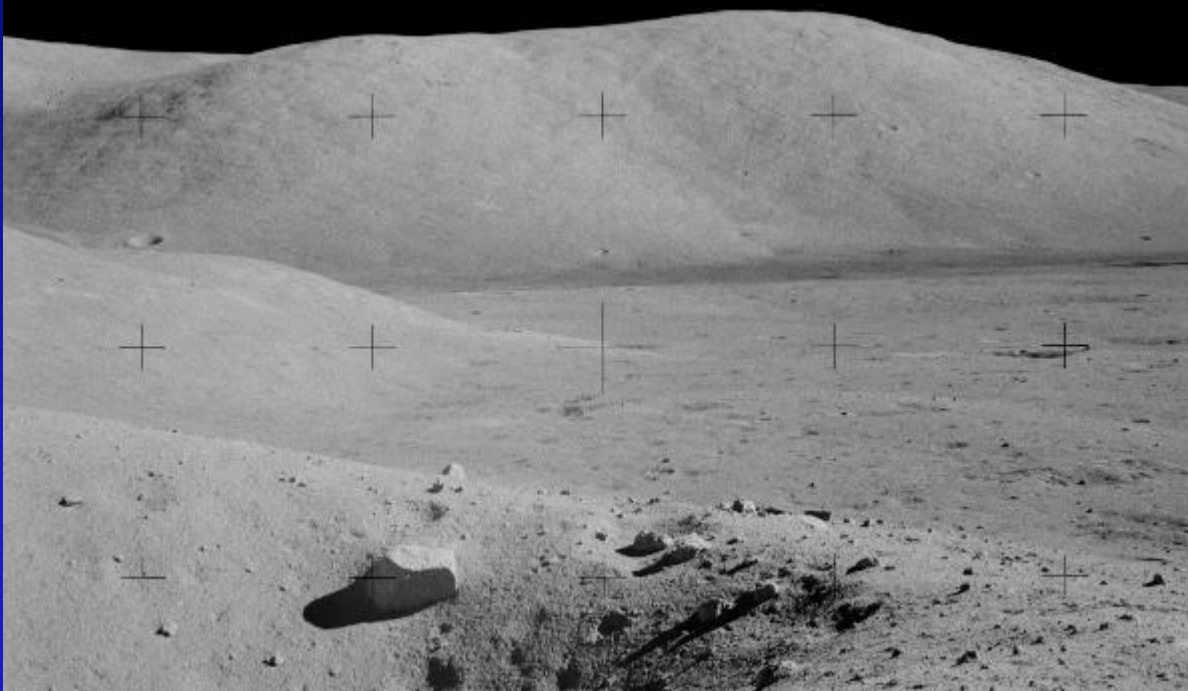
Alan Howard, 2007

(Geomorphology)



Raindrops on Earth = Impacts on the Moon

Typical rate of topographic change is $\sim 200 \times$ less than measured in the western US.



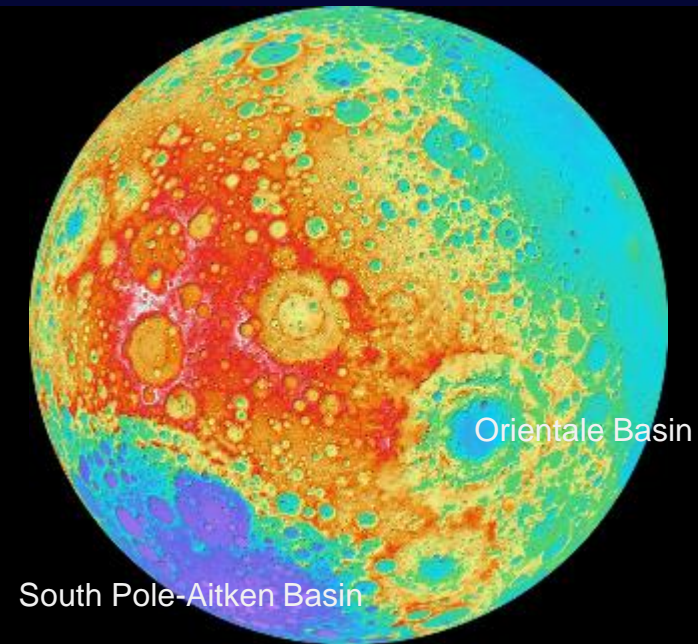
North Massif, Apollo 17



Other Big Science Questions About the Moon

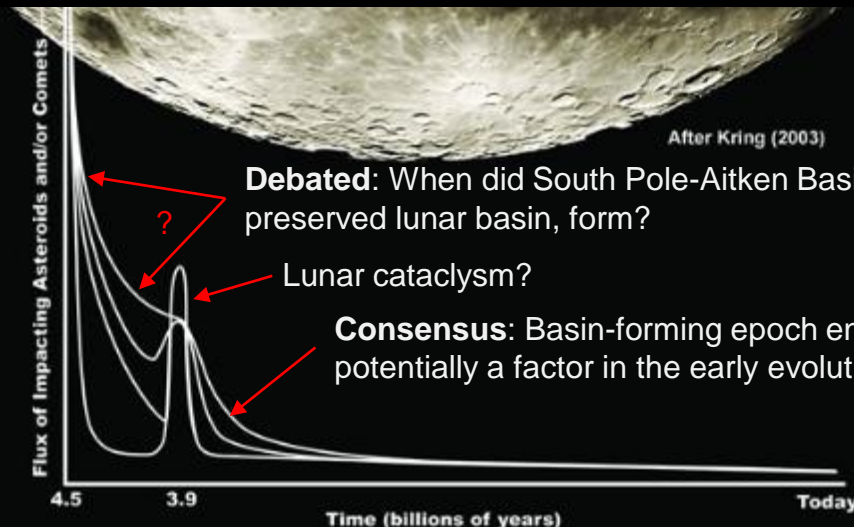
Impact History of the Inner Solar System

From the Moon, we learn about Earth, Mars, etc.



SPA @ ~4.1 Ga:
42 basins formed within
300 Myrs – much more
intense Lunar Cataclysm.

SPA @ ~4.5 Ga:
42 basins formed over
700 Myrs – less intense,
or no, Lunar Cataclysm.



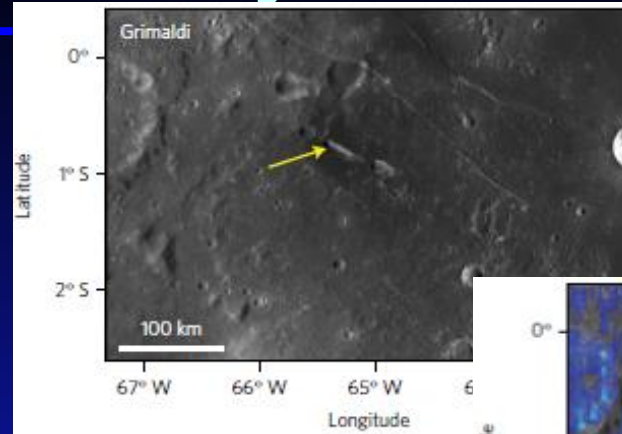
Volcanic and Volatile History of the Moon



2014 Holuhraun eruption, Iceland

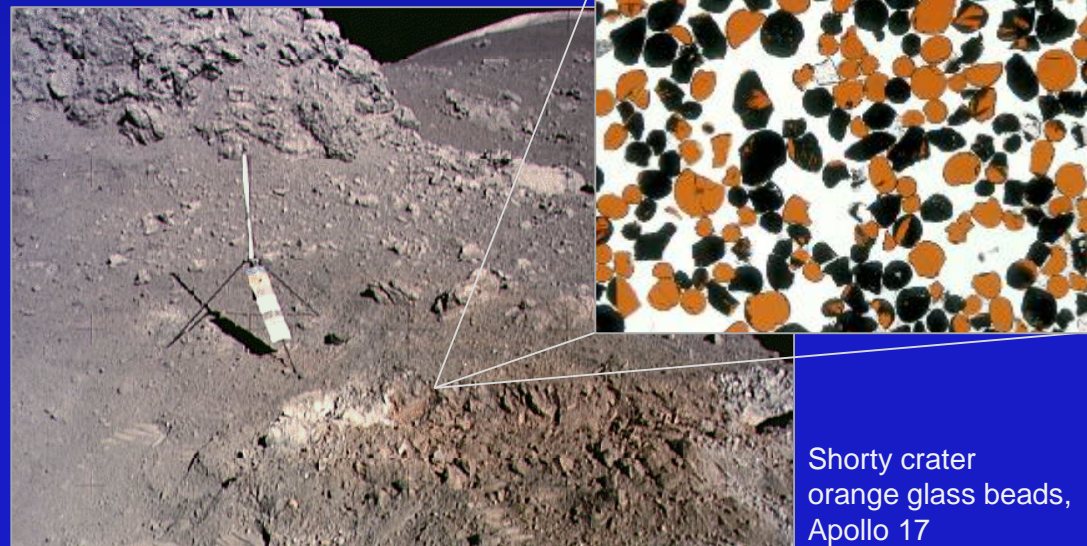
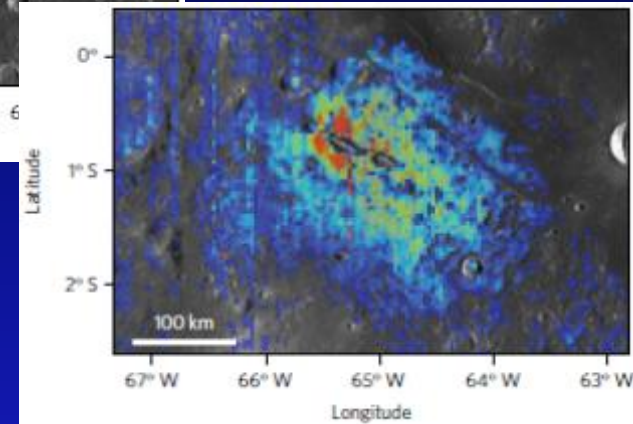
Fiery eruptions formed deposits of glassy beads collected during Apollo missions.

Compositions indicate Moon contained more volatile materials than previously thought.



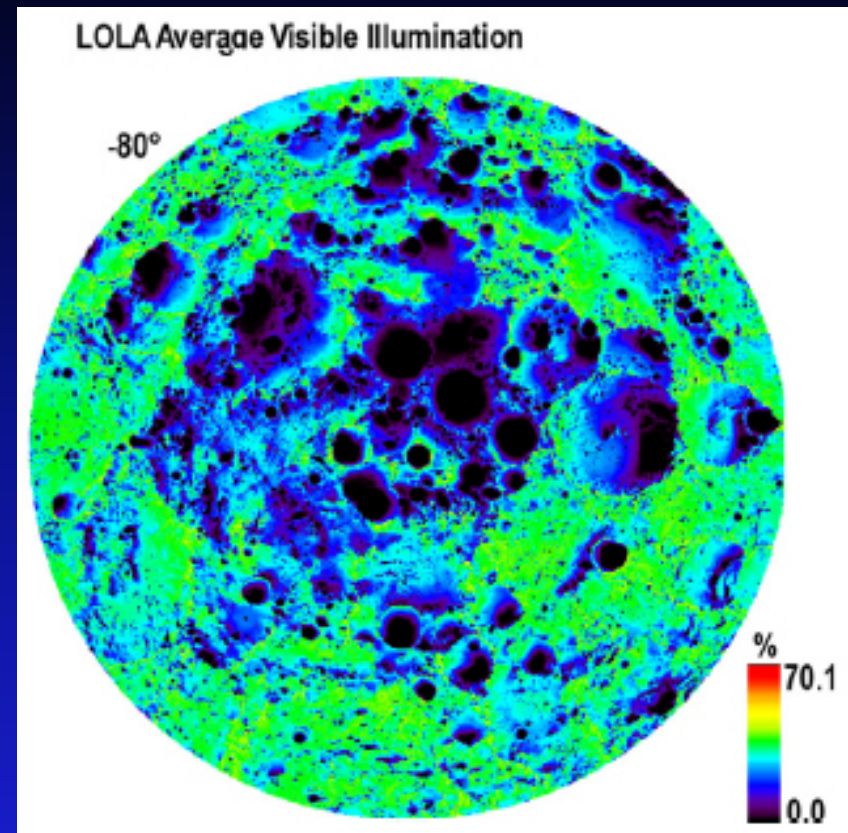
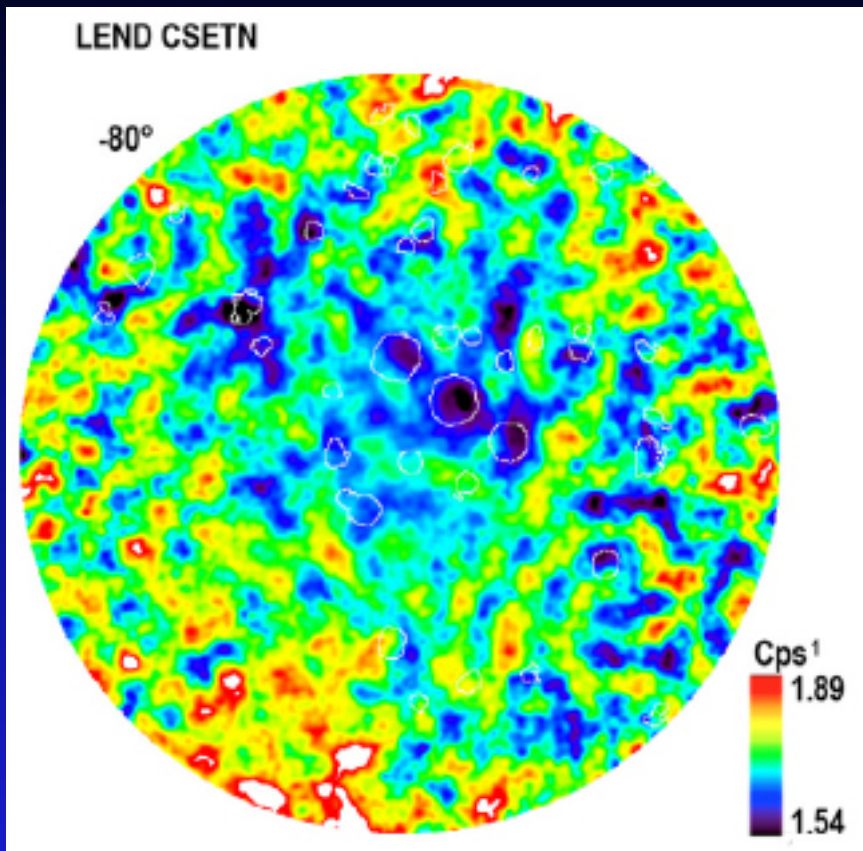
Pyroclastic deposit at Grimaldi as identified from Lunar Reconnaissance Orbiter Camera and Moon Mineralogy Mapper.

Water content observed on the lunar surface, ranging from $<0.005\%$ (blue) to $>0.03\%$ (red).



Shorty crater orange glass beads, Apollo 17

Polar Volatile Resource Distribution on the Moon



LP and LRO see enriched hydrogen (left) in permanently shadowed regions near the Moon's poles. These may represent ice deposits that could be used as resources for human exploration of the Moon.

Where did these deposits come from, how much water is there, and how is it distributed?

Summary

- Exploration of the Moon has a glorious history, but it has also just begun.
 - Next ten years are an exciting opportunity to build a new, sustainable program of human and robotic exploration.
- Big open questions remain about:
 - Lunar formation, differentiation.
 - Volcanic processes and volcanic history.
 - Chronology of large impacts.
 - Resources for human exploration.